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Review of sugarcane trash recovery systems for energy cogeneration in South Africa

Jeff Smithers

School of Engineering, University of KwaZulu-Natal, South Africa

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ABSTRACT

Biomass is a potential sustainable source of energy. Approximately one-third of the energy available from sugarcane is contained in the tops and leaves (trash), which are generally either burnt prior to harvesting or are not recovered from the field. Based on results reported in the literature and assuming a 50% trash recovery efficiency, it is estimated that 1.353 million tons of trash is available annually for cogeneration in South Africa, which could potentially produce 180.1 MW over a 200 day milling season. Studies in Brazil and Australia have shown that the most efficient way of recovering the tops and leaves for cogeneration of power at sugar mills is to use a chopper harvester with the separation of cane stalks and trash on the harvester either fully or partially turned off. In South Africa more than 90% of the sugarcane crop is burnt and manually harvested and hence new systems are proposed to recover the trash and to transport the material to the mill.

Contents

E-mail address: smithers@ukzn.ac.za

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1. Introduction

As a consequence of the rising global demands for energy, the cost volatility, the dwindling reserves of fossil fuels and the impacts of the use of fossil fuels on greenhouse gas emissions have all resulted in biomass to be considered as an important, alternative source of energy [6,14,41]. The environmental impacts of the growing demand for petroleum derived fuels can be mitigated by the use of lignocellulosic biofuels [15]. Not only is it being realised that biomass presents a potential renewable source of energy opportunity that could provide an alternative to the use of fossil resources and reduce human dependence on fossil fuels, but also that it will impact positively on many environmental issues, including the minimisation of the production of greenhouse gases [6]. The high production of biomass reported by Muchow et al. [39], combined with the efficient use of water by sugarcane in terms of biomass produced per unit of water, makes sugarcane an ideal energy crop [6].

The sugarcane industry has been moving from sugar production to sugar and energy production with the development of cogeneration and ethanol plants and this will result in the cane energy content and energy yield per hectare and per ton of cane becoming important parameters which will be used for variety selections in the future, and being a part of future payment systems [7]. The agronomic benefits and the potential energy resource of sugarcane tops and leaves, commonly referred to as trash, have been recognised and the development of new harvesters has promoted the utilisation of these benefits [44]. In a study to investigate diversification options for the sugar industry in Australia, whole crop harvesting to maximise electricity cogeneration was identified as the venture with the highest priority [61]. The potential for the sugar industry in South Africa to mitigate against climate change by producing renewable cogenerated electricity and fuel ethanol was highlighted by Govender [19].

Sugarcane bagasse (fibrous fraction of cane) is the most abundant crop residue produced globally and this resource can be increased by harvesting the sugarcane leaves and tops [5]. With the improvements in sugarcane harvesting and cogeneration technology, bagasse and sugarcane trash have become important sources of bio-energy [1]. The use of sugarcane trash has the added benefit of not competing as a food source and has a similar energy content as bagasse per unit weight, but is frequently burnt off to facilitate harvesting of the stalks [1]. The sugarcane trash, which is currently mainly burnt prior to harvest, is a significant source of energy [55,56] and sugarcane has the highest rate of energy production per hectare (0.5–2 GJ ha^{-1}) [5]. Despite the potential to generate heat and power from bagasse, the potential for the cogeneration of electricity remains largely unexploited [5].

Over 9 GW of worldwide generation capacity is currently provided by biomass based electricity schemes. Sugarcane bagasse and sugarcane trash have the potential to provide a significant amount of biomass for electricity production, and the potential becomes much higher with the use of advanced cogeneration technologies [38]. Sugarcane leaf biomass has a high calorific value which has a low production of micro-pollutants when processed with improved technology and thus represents a significant source of energy which can reduce environmental issues associated with energy generation [53]. It has been estimated in Brazil that energy from residual biomass can supply energy to 7.0 million people and that 5.5 million people can be supplied with energy from bagasse [53] and sugarcane biomass is seen as one of the most readily available energy sources in Brazil [37]. However, high recovery costs will be incurred in gathering, baling, transportation, chopping and technology to utilise the trash on a large scale [37]. The sugarcane transport infrastructure currently used to transport the sugarcane stalks to mills can be utilised to make the trash an economically viable energy source for boilers, irrigation power and to export to the local area [41].

Not burning sugarcane prior to harvest has environmental benefits and the residual biomass can help reduce the global energy deficit, but the feasibility of extracting the energy from the currently unutilised biomass has not been proven [53]. Many countries are considering the use of sugarcane as a potential source of renewable energy. For example, in El Salvado it is projected that 55 MW of power can be generated during the four month cane crushing season from 346,503 t of sugarcane [69]. In Mauritius, 10 out of 11 sugarcane processing mills export electricity to the grid during the milling season. This generation of electricity was promoted by government incentives which focussed on the optimum use of bagasse to generate electricity and by the use of sugarcane trash for electricity generation [11]. Efficient energy production from biomass has the potential to offer new development paths, sustain rural livelihoods, reduce dependence on imported energy sources and reduce green house gas emissions in sub-Saharan Africa, particularly in Malawi, Mozambique, Tanzania and Zambia, which have the greatest potential to achieve this after accounting for food production and resources constraints [24]. An analysis by Johnson et al. [24] showed that in South Africa 1.2% of the energy provided by petrol could be supplied by ethanol in 2005 and this could rise to 7.4% by 2030.

The escalating real cost of energy and advances in technology to produce bio-energy is starting to make the bio-energy cost competitive and this presents opportunity to the sugar industry in South Africa to generate income from co-generation and fuel alcohol [68]. Government commitment to develop renewable sources of energy, protection of jobs, reducing green house gas emissions from fossil fuels and the need for energy security will aid the sugar industry to produce bio-energy [68].

With the exception of Brazil, sugarcane is produced primarily as a food crop although many countries are investigating energy options as well [26]. Thorburn et al. [62] discuss the impact of changing the production of sugarcane from a purely sugar focus to a sugar and energy focus which may require changes to farming systems and the use of feedstock from other biomass to ensure year round cogeneration potential. Integrated supply chain models are necessary to enable the assessment of the impacts and to benefit from participation by stakeholders [62]. Harvesting, loading and transport are approximately one third of the cost of cane at mills in Brazil [21].

Given the above, it is evident that the recovery of some of the sugarcane trash for energy production, while retaining a trash blanket, has much potential. However, the recovery of the trash and the low bulk density of the trash will have cost impacts on harvesting, transport and processing of the biomass.

The objective of this paper is to review the potential energy available from sugarcane, the potential yield of sugarcane trash and systems used to recover the trash from the field. These results are used to assess the potential trash yield in South Africa, the power that could be generated from the trash, and to suggest potential trash recovery systems for use in South Africa based on systems used internationally. Research needs from this analysis are also summarised.

2. The sugar industry in South Africa

In South Africa, the crushing season starts in April, is eight to nine months long and finishes in November/December. Approximately 20–22 million tons of cane, produced from approximately 430,000 ha are delivered to 15 factories varying in size between 90 $t.h^{-1}$ and 550 $t.h^{-1}$, with most mills averaging approximately 300 $t.h^{-1}$ or 1.5 million tons of cane per annum [33,68]. There is evidence that continuous cropping with sugarcane has adversely affected soil productivity in South Africa and resulted in a plateau in yield output between 1971 and 1998 [36] and with a declining trend in the annual tons of cane crushed since then [58].

Sugarcane is grown under a wide range of conditions in South Africa, from steep to flat terrain, with 0.9–1.5 m row spacing, 12–24 month cutting cycles and cultivation under dry land and irrigated conditions [32]. Most of the sugarcane is cut by hand ($>90\%$) in South Africa due to the availability of labour and steep topography with a large proportion grown on terrain not suitable for mechanical harvesting [2,33].

Total internal power requirements for a raw sugar factory are between 35 and 40 kWh t^{-1} of cane processed [68]. Most sugar factories in South Africa are designed to burn bagasse inefficiently so as to avoid the need for a costly bagasse disposal system. Others are fitted with a back-end refinery (Malelane, Pongola, Umfolozi, Gledhow and Noodsberg), or are exporting bagasse (Malelane, Felixton, Gledhow, Maidstone and Sezela) and burning significant amounts of coal. Mills at Komati, Felixton and Maidstone were doing some cogeneration with the selling price varying from 3 to 49 c kWh^{-1} depending on the time of year, the time of day and the electricity buyer [68].

The sugar industry in South Africa produces an average annual crop of 20 million tons of sugarcane which contains biomass with an energy equivalent of 1.75 million tons of coal which could potentially produce 1600 MW of electricity. With adequate investment, the biomass could produce 600 MW of electricity by 2016 which represents 20% of the 10 000 GWh target of renewable energy set for South Africa [64].

3. Cogeneration of electricity from sugarcane trash

Sugarcane mills can cogenerate electricity from the bagasse derived from the processing of the cane stalks and Beeharry [4] concluded that the use of cane trash has the potential to contribute significantly to the exportable energy from a sugar mill. WADE [65] lists the potential benefits of cogeneration from bagasse as economic, social and environmental, which includes savings in CO_2 production and in infrastructure costs, while an analysis by Beeharry [3] confirmed the potential of sugarcane bioenergy systems to generate electricity with a reduced release of CO_2 into the atmosphere compared to conventional fossil fuel systems. Johnson et al. [24] reported that a reduction in total CO_2 emissions by 17%, a GDP increase of 1.3%, and a decrease in unemployment by 2% could result from the cogeneration of electricity from sugarcane.

Beeharry [3] showed that energy from sugarcane could be increased from 41 kWh t^{-1} cane, which was based on current sugarcane production practices in Mauritius, to 276 kWh t^{-1} cane if all the biomass was utilised. This led Beeharry [4] to conclude that the use of cane trash has the potential to contribute significantly to the exportable energy from a sugar mill.

It is important to consider the ratio between energy consumed and energy captured in the feedstock when considering any potential energy feedstock [6]. Analyses by Botha [6] show that the energy required to produce sugarcane is significantly lower than for most other biomass sources and the energy produced from sugarcane is almost 50% cheaper than the cost of production from coal if carbon capture and storage is taken into consideration. Processed trash is a cheaper source of fuel to a sugar mill compared to crude oil or coal with carbon capture [6].

However, harvesting the whole crop, i.e. using the additional fibre in the trash to fuel cogeneration, maximises the output of energy but will impact on the whole value chain from production, harvesting, transport and milling [62]. The agronomic impact of removing the trash from the field and harvesting and transport, storage, boiler design and fuel mixing all require further investigation [4] and the removal of trash from the field could have an impact on the fertiliser requirements and hence on crop growth [12].

Challenges to recovering trash for cogeneration of electricity include currently accepted farmer practices, pricing mechanisms, low bulk density, collection efficiency, and soil in the trash [47].

4. Energy from sugarcane

There is a shift from producing cane for sugar to producing cane for energy [26]. It is estimated that less than 30% of the total primary energy content of sugarcane is converted into the two forms of useful energy, i.e. electricity and ethanol [26].

The primary energy from sugarcane is estimated to be approximately 7400 MJ t^{-1}, as shown in Table 1. Assuming that 1 t of oil contains approximately 42 GJ of energy, the cane contains 17.6% of the energy value of oil on a mass basis [26]. The energy value of 1 t of cane is equivalent to 1.2 barrels of crude oil [43] and is equivalent to 95–114 barrels of crude oil per ha [47]. The moisture content and the technology used for energy production are the two main factors which determine the amount of energy that can be extracted from bagasse [65]. In order to estimate net energy produced, harvesting, processing energy and extraction costs must be taken into account.

Utilising sugarcane trash would potentially double the energy for cogeneration [49]. Dry sugarcane trash contains 28% of the potential energy in sugarcane and has the potential to reduce the national energy deficit by 50% in India [47]. The energy present in recoverable dry leaf (excluding the tops and green leaf) is equivalent to approximately ten tons of coal per hectare and the energy available in the trash is approximately one third of the total energy available, with sucrose and bagasse both containing approximately a third of the total energy [41]. The dry leaves have a calorific value of 12 GJ per ton which as approximately 45% that

Table 1
Primary energy from 1 t of sugarcane [26,1].

Component (dry basis)	Energy (MJ t^{-1} of clean cane stalks)
142–150 kg of sugar	2257–2500
135–140 kg of stalk fibres	2184–2400
140 kg of leaf fibres	2184–2500
Total (422–430 kg)	6625–7400

of thermal coal [41]. The energy content of bagasses and trash from various studies are summarised in Table 2 and indicates that the energy in trash ranges from 8.0 to 18.3 MJ kg^{-1}.

5. Trash recovery

The amount of trash from sugarcane is dependent on factors such as harvesting system (burnt or unburned cane), topping height, cane variety, age of crop (stage of cut), climate and soil. The trash left in the field after harvesting is a function of the amount of tops and leaves available in the field prior to harvesting and of the harvesting system used [44,51,47].

5.1. Potential trash yield

Up to 40% of the total biomass of sugarcane can be made up of foliage [47]. Rein [49] reports on studies where tops and leaves make up from 188 to 350 kg per ton of total cane mass and from 110 to 170 kg dry matter per ton of whole stalk cane and recommend that 150 kg dry matter in leaves and tops per ton of clean, whole stalk cane can be assumed.

On average 15–20 t ha^{-1} of trash are produced [47]. Núñez and Spaans [42] found that 17.3 t ha^{-1} of trash were left in the field after green harvesting in Ecuador compared to 3.7 t ha^{-1} after burnt harvesting. Hassuani [20] reports that the cane varieties grown in Brazil produce from 110 to 170 kg dry matter per ton of cane, with an average yield of 140 kg t^{-1}.

From 10 studies reported in the literature, Paes and de Oliveira [44] report that the average trash yield was 14.1 t ha^{-1} from an average cane yield of 77.2 t ha^{-1}. Average yields of trash and cane of 14.4 t ha^{-1} and 104.0 t ha^{-1} respectively were found by Paes and de Oliveira [44] for three popular cane varieties grown in Brazil and for three stages of cut. The amount of trash left in the field after green cane harvesting was found by Manechini et al. [28] to range from 6.7 to 14.9 t ha^{-1} dry matter, dependent on the cane variety, sugar cane field yield and harvester cleaning efficiency

In Argentina, Romero et al. [51] found that the quantity dry trash per hectare before harvesting increased with increasing cane yield. The quantity of dry trash before harvest ranged from 6.9 to 16.0 t ha^{-1}, depending on varieties and production levels. The amount of dry trash increased linearly with cane yield (significant at $p=0.05$) and, up to a cane yield of 85.9 t ha^{-1}, the increase rates among different varieties of cane were similar and ranged between 14.6 and 16.2 kg of potential dry trash per ton of cane yield. This led Romero et al. [51] to conclude that the yield of trash after green harvesting can be estimated using cane yield.

5.2. Trash estimation from cane yield

Donaldson [12] found that the average ratio of leaves (excluding tops): cane stalk was 11%, which is lower than the ratio of 17% reported for dry land sugarcane production by Thompson [60], which included stalk tops. Donaldson [12] also presented results for the estimation of the dry mass of stalk tops. Table 3 contains a summary of the trash yield as a function of cane stalk yield reported in a number of studies. Thus, knowing the cane yield, the sugarcane trash yield can be estimated using the results from Table 3.

6. Sugarcane harvesting systems

Harvesting and haulage are the most expensive operations in sugarcane production [35] and constitutes approximately 30% of the cost of sugar production in Southern Africa [66]. Harvesters have been traditionally viewed as retrievers of sugar bearing stalks and discard as much of the extraneous material as possible, but are increasingly seen as sugarcane sorters as well with the ability to collect part or all the trash [9]. Hassuani [21] reports that, prior to 2003, mechanical harvesting of cane in Brazil accounted for less than 20% of the harvested cane, with manual harvesting and mechanical loading of the cane harvested onto trucks being the most common system.

Green cane harvesting can be done by two systems [34]:

- manual harvest of whole stalks followed by manual or mechanical loading, or
- a fully mechanised chopper harvesting system.

The topography and soil conditions influences the type of extraction system used with small in-field trailers and cane is transferred to road vehicles at a loading zone in terrain where large vehicles cannot enter the field [66].

Manual sugarcane harvesting is not an attractive form of employment and labour is becoming a constraint for manual harvesting in South Africa [33,27]. This is a result of rising labour

Table 2
Summary of energy content of sugarcane bagasses and trash.

Component	Moisture content (%)	Energy (MJ kg^{-1})	Reference
Trash and tops	30	11.6	De Beer et al. [9]
Trash and tops	10	15.8	De Beer et al. [9]
Bagasse and trash	Dry	17.0	Beeharry [4]
Trash		10.4–15.0	Prabhakar et al. [47]
Bagasse		13.4	Duku et al. [14]
Bagasse	50	8.0–9.9	Filho and Badr [18] and Beeharry [4]
Leaves	Dry	12.0	Norris [41]
Trash	20-30	16.1–18.3	Prabhakar et al. [47]
Trash and tops	Dry	15.1	Botha [6]

Table 3
Summary of dry trash yield estimation from cane stalk yield.

Region	Cane Stalk Yield (t ha^{-1})	Total Cane Trash		Reference
		(t ha^{-1})	(% Cane stalk)	
South Africa			20.0–35.0	De Beer et al. [9]
South Africa	156	19.3	12.3	Donaldson [12]
Brazil			11.0–17.0	Hassuani [20]
Various	77.2	14.1	18.3	Paes and de Oliveira [44]
Various			11.2	Fernandes and Oliveira [70]
Brazil			13.8	Paes and de Oliveira [44]
Brazil			14.0	de Carvalho Macedo et al. [10]
Australia			19.5	Thorburn et al. [61]
General			15.0	Rein [49]

aspirations, growth in the industrial sector and the impact of HIV/AIDS in South Africa. Meyer et al. [34] report similar labour shortages in India and Reunion Island. Manual harvesting is often preferred in South Africa due to the cost of mechanical harvesters and the unsuitability of mechanical harvesters to operate on steep slopes [27]. In Brazil, a slope of $< 12\%$ is considered to be mechanically harvestable [20].

6.1. Manual harvesting systems

More than 80% of the cane is burnt prior to harvesting and more than 90% of the cane in Southern Africa is harvested manually [66]. In South Africa two basic systems are used to harvest the crop manually [33,66]:

- cut and stack green or burnt cane, or
- cut and windrow green or burnt cane for subsequent mechanical loading.

The stacks or windrows are loaded mechanically [66]. When harvesting green cane manually the trash is removed and the stalks are topped, while for burnt cane only the tops are removed [31]. The cut cane is then bundled for transport [31]. Stacked cane can be chained and winched onto self-loading, low-level tractor-drawn field trailers. These trailers carry approximately 5 t and are generally used in fields where the topography or soil conditions prevent larger units from operating. Grab loaders are used where cane is cut and placed in small stacks or bundles [66]. Where cane is laid in windrows, push-pile-grab loaders are used to push the cane into bundles which are then loaded into trailers [66]. The energy expenditure for cutting green cane is 10% more than for cutting burnt cane [57].

6.2. Semi-mechanised harvesting systems

The Agricultural Engineering Department at the former South African Sugar Experiment Station (SASEX) investigated a number of mechanised harvesting systems [30] which included:

- whole stalk transverse windrowing machines,
- whole stalk linear windrowing machines,
- whole stalk bundling machines, and
- chopped cane harvesters.

Cutting, topping and trashing operations are performed manually and the cane is then either placed in 3–6 t stacks and the stacked cane is winched onto tractor drawn side or rear self-loading trailers by a winch mechanism. Alternatively, the cane from four to six rows is placed in windrows at right angles to the row direction and the windrowed cane is loaded mechanically using slewing or non-slewing loaders which can be self-propelled or mounted onto a tractor [31].

Many sugarcane industries require a harvesting system which falls between manual and fully mechanised harvesting [34]. Relatively simple cutting attachments mounted on standard tractors or self-propelled machines can be used to mechanise the cutting operation. The cane can be deposited in windrows at right angles to the row direction or left in linear windrows parallel to the row direction. In both cases the cane can be collected manually or mechanically, as described above [31].

In order to increase labour productivity and to reduce the exertion required by manual cutting, Lyne et al. [27] developed a brush cutter with a redesigned blade configuration. A work and ergonomic study was conducted on a commercial farm for both the mechanical and conventional manual harvesting systems. The results show that the brush cutter is less demanding than the conventional system and the costs compare favourably with the conventional manual system. Lyne et al. [27] concluded that the mechanical system was a viable alternative to the conventional method of manually cutting sugarcane.

6.3. Fully mechanised harvesting systems

Both whole stalk and chopper harvesters are used for mechanical harvesting of sugarcane.

6.3.1. Whole stalk harvesters

Self-propelled whole stalk harvesters cut and top one or two rows of cane and deposit the whole sticks of cane from 4 to 6 rows into a single windrow using a flexible piling arm. After windrowing, the cane is burnt and mechanically loaded into road transport vehicles, using high capacity push-pile loaders [31].

Whole stalk harvesters have been used extensively in Louisiana and comparisons with chopper harvesters showed no significant differences in harvesting rates, although the losses from whole stalk harvesters were larger in wet weather and when the cane was lodged [50]. The use of infield mechanical de-trashers resulted in an additional infield operation [50].

6.3.2. Chopper harvesters

Modern chopper harvesters are capable of harvesting all but very heavy green cane crops [34]. Combine chopper harvesters base cut and top one or two rows of cane and chop the cane stalks into billets of approximately 300–450 mm in length. Cane tops missed by the primary topper, trash and other extraneous matter are removed by harvester extractor fans and the billets are delivered into trailers (haul out vehicles) travelling alongside the harvester. Both burnt and green cane can be harvested by chopper harvesters which are capable of handling yields in excess of 150 t ha^{-1}. Chopper harvesters handle lodged cane better than whole stalk harvesters, but harvesting rates of green cane are reduced by 30–40% compared with harvesting burnt cane [31].

7. Trash recovery systems

The reductions in sugarcane yield and pests associated with green cane harvesting with trash recovery means that trash recovery has to have economic benefits [22]. However, the equipment, labour and other farmer priorities limit the recovery of trash by farmers, which also conflicts with efforts to maintain soil productivity (agronomic benefits) and to minimize soil erosion. Hence, trash recovery by farmers must be directly linked to economic benefits [52].

Various efficiencies of trash recovery have been reported in the literature. Schembri et al. [55] assumed that 50% of the trash could be recovered from the field, Filho and Badr [18] estimate the at least 25% of the field trash can be recovered, Rein [49] estimate the recovery efficiency to range from 56% to 84%, and Seabra and Macedo [56] estimate the trash recovery efficiency to be 40%.

Trash recovery systems include baling, hay harvesters, whole stick harvesting and trash collected by the sugarcane harvester [22]. Both de Carvalho Macedo et al. [10] and Hassuani [21] report on the testing and analysis of four trash recovery routes, as shown in Fig. 1.

Routes A and B involve whole cane harvesting with the cane and trash separated at the mill (Route A) or separated in the field with the trash collected with another infield operation (Route B). Routes C and D involve the use of a chopper harvester, with the trash and cane either separated in the field by the harvester (Route C), with an additional infield operation to collects the trash, or the extractor fans on the harvester set such that the loss of cane and

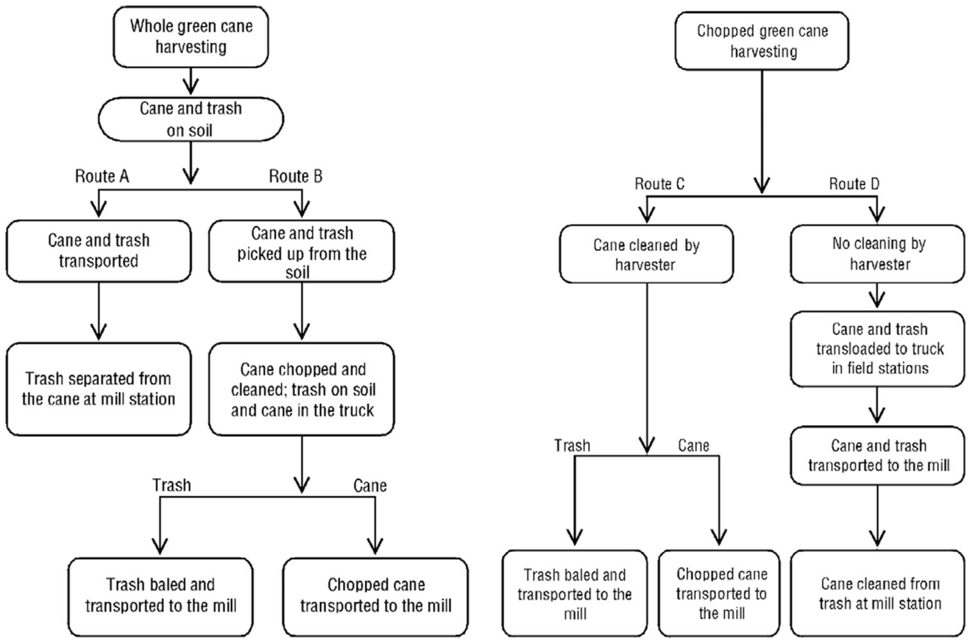

Fig. 1. Selected routes for sugarcane harvesting with trash recovery [10].

trash are both minimised and the combined trash and cane are transported to the mill and only separated at the mill (Route D). Routes A and D require equipment to separate cane from trash at the mill and also requires equipment to process the trash at the mill, either in loose or baled form.

7.1. *Whole stick harvesters*

Much development of machines to perform whole stick harvesting has been conducted [34]. The advantages of whole stick harvesters are fewer losses compared to chopper harvesters, and that the harvesting and transport operations are independent of each other [40]. Prabhakar et al. [47] report that 95% of the trash can be recovered by harvesting the trash with the cane.

In order to implement Routes A and B in Fig. 1, Neves [40] developed a “Two Row Whole Stalk Cane Harvester” to place harvested cane sticks at right angles to the cane rows, as no commercial harvester was capable of doing this. Despite modifications made to the harvester, it could not operate satisfactorily in fields with cane yields greater than 70 t ha^{-1}, or in fields where the cane was lodged, or where the topping height was > 2.4 m.

Hassuani [21] report that most mechanised whole stalk cane harvesters leave the stalks parallel or diagonal to the furrows, which results in increased soil compaction and machine wear caused by loaders and trucks forced to cross the rows during the loading operation. These operational problems have resulted in very limited adoption of mechanised whole stalk cane harvesters [21]. In the study reported by Marchi et al. [29], the use of whole stick harvesters for trash recovery (Routes A and B) was discontinued as a consequence of the poor performance of the whole cane harvester when operating with green cane in high productivity areas.

7.1.1. *Cane and trash separated at the mill (Route A)*

Route A consists of the whole stalk cane harvester leaving the stalks in mats on the ground which are collected by a loader-transporter which stockpiles the stalks which are then loaded for transport by a conventional grab loader [29]. The advantages of this system include the following [29]:

- Independence between harvesting and cane loading operations, thus allowing continuous operation of the harvester and avoids harvesting operations having to stop due to a lack of trucks.
- No stool damage and infield compaction is experienced as no trucks are required in the field.
- Truck loading operations can be optimised as the loading is independent of the harvester.

The results from the evaluation of Route A showed that the harvester could not cope with cane yields > 70 t ha^{-1} or when the cane was lodged and a new machine design was required to overcome these problems [29].

7.1.2. *Cane and trash separated infield (Route B)*

As shown in Fig. 1, green whole stalks are harvested in Route B with cane and trash left on the soil, followed by the collection using a continuous loader which also chops and separates the cane and trash with the cane loaded into trucks and the trash is left in field to be baled in a subsequent operation and then transported to the mill [29].

7.2. *Chopper harvesters*

Chopper harvesters can cut the tops off and then chop the remaining portion of the plant into billets. The cane billets are separated from the trash in the harvester and the trash is blown back onto the field. On average, 68% of the trash is blown out of the harvester and 32% of the trash is transported to the mill as extraneous matter [10]. By turning off the extraction fans, both the cane and trash can be recovered and separated at the mill, but cane tops are generally left in the field due to their low calorific value and to protect the soil [22].

Whiteing et al. [67] investigated losses from harvesting green cane with a chopper harvester and found that harvester designs at that time were limited in their ability to effectively clean cane and minimise cane loss at high harvesting rates. Chopper harvesters are only capable of separating approximately 75–80% of the trash

from the cane and hence approximately 20–25% of trash is taken to the mill together with the cane as extraneous matter [20,22]. Trash blown back to the field can be baled 2–3 days later. An alternative to the above approach is to not separate the cane and trash in the harvester and to transport cane and trash together to the mill, which results in approximately 5% of the trash being left in the field [20].

Hassuani et al. [22] report on the development to shred the trash in the chopper harvester, where the conventional primary extractor fan on the harvester is replaced by a new fan design and a two stage counter rotating set of multiple shredding blades. This will result in not having to collect the trash during a second operation and the shredded trash will pack to a higher bulk density and be suitable for the boilers at the factory.

The field capacity of a chopper harvester in burnt cane is approximately 700 t day^{-1} [21]. The impact on harvester performance of turning the extractor fans off resulted in a 3% decrease in losses and reduced harvester capacity by 27% [10].

7.2.1. Cane and trash separated infield (Route C)

As shown in Fig. 1, in Route C green cane is harvested with chopper harvesters with trash separation in the harvester, i.e. the extractors are working normally and conventional cleaning takes place. The chopped cane is transported to the sugar mill, and the trash is baled and also transported to the mill [29].

The mass balance for trash recovery for Route C with an average 68% harvester separation efficiency and 84% baler pickup efficiency resulted in 88% of the potential trash recovered [10].

7.2.2. Cane and trash separated at the mill (Route D)

As shown in Fig. 1, Route D harvests green cane with a chopper harvester with the extractor fans turned off and the chopped cane and trash are transported to the sugar mill where they are separated at a cleaning station [29]. This resulted in a trash recovery of 95% from Route D [45]. An alternative to this was evaluated where, with partial cleaning, approximately 50% of the trash was left in the field and this reduced the trash recovery to 71% for the partial cleaning route, with 21% of the trash left in the field [45].

7.3. Infield trash collection after harvesting

For both Routes, B and C, the trash remains in the field after harvesting and additional operations are required to collect and increase the density the trash prior to transport. Both balers and continuous loaders have been used to collect the trash and other densification systems have been investigated.

7.3.1. Baling (Routes B and C)

Balers increase the density of biomass and the standardisation and optimisation of the equipment reduces the cost of residue collection and transport [52]. Both square and round balers have been used successfully to bale cane trash and tops, but need to be made more robust. According to de Beer [9], round balers are more economical given the higher tonnage baled per hour and have reduced maintenance and breakdowns and lower twine requirements compared to square balers.

de Carvalho Macedo et al. [10] and Sarto and Hassuani [52] investigated both round and square balers and selected large (200 kg) square balers based on baling efficiency, ability to handle trash and cane stalks, productivity, bale handling, transportation and storage costs. Hassuani [20] and de Carvalho Macedo et al. [10] reported on the performance of a square baler when baling cane trash that had (i) not been raked, (ii) been raked once into windrows or (iii) been raked twice into larger windrows. de Carvalho Macedo et al. [10] suggest that a baling recovery efficiency of 70% should be used in trash recovery feasibility studies, even though 84% was obtained in field results [10,20,52]. Prabhakar et al. [47] found that between 56% and 84% of the trash can be collected by raking and baling the cane trash.

Hassuani et al. [22] and Sarto and Hassuani [52] assessed the performance of round and square balers. They found that small rectangular balers have a higher productivity, are better able to deal with trash and pieces of cane left in the field, and utilise transport space more efficiently. As a consequence of the difficulty of the in-field recovery of a large number of small rectangular bales, they concluded that large rectangular bales should be used. They recommended two raking operations to improve baler performance and to minimise damage to the pick-up system due to soil contact. Despite their results, Hassuani et al. [22] noted that mills in Brazil that were recovering trash through baling usually use round fixed drum balers due to their availability, simpler maintenance, and the lower cost of the round balers.

Paul and Krishnamurthi [46] conducted experiments in India to assess the harvesting of cane trash. These included the use of both square and round balers with the trash windrowed both manually and by a mechanical rake. The output of both types of balers were found to be similar, but the transport efficiency of the round bales was lower as specialised trailers had to be used and mechanical loaders were required, whereas the square bales could be manually loaded. The performance of the balers declined in the second season due to wear and maintenance issues.

Paul and Krishnamurthi [46] found that tractor-drawn ‘finger wheel rakes’ were not suitable for manually harvested whole length trash and a PTO driven rake with a single vertical rotor with spring tyne arms was found to be more successful. It was noted that in sandy soils with cane planted at shallow depths (0.15 m), windrowing operations resulted in stool uprooting. In order to reduce choking during baling, speeds were reduced to between 0.82 and 2.33 km h^{-1} which resulted in a maximum baling capacity of 3.14 t h^{-1}. For distances <15 km from the mill, the loose trash was collected, bundled and transported using bullock carts and small tractor-trailer combinations. It was found that 20–30% of the trash remained after bailing which eliminated the need for burning.

Problems with baling trash include the time required to dry the trash to less than 20% moisture content, chocking problems during pick up, picking up of soil, excessive wear on the machine and the unreliability of the balers, especially the twine tying system [20,22,52]. Paul and Krishnamurthi [46] concluded that the viability of using balers to densify the trash for transport was feasible, but the throughput of the equipment needs to be increased for a viable system. It was also noted that farming systems and layouts needed to be adapted to suit mechanised operations and the collection of soil with the trash and baler pickup and chocking were experienced.

Traditionally balers have been used to densify hay but a prototype has been developed to bale woody biomass [13]. Savoie et al. [54] developed a round (1.2 m high by 1.2 m diameter) “Biobaler” capable of harvesting and baling material from short-rotation woody crops with stem diameters <150 mm. Round bales weighing 300–500 kg were harvested at rates ranging from 10 to 45 bales per hour, dependent on crop yield, soil firmness, and stem diameter.

In a study of the costs of whole crop harvesting vs. cane stalk harvesting and the baling of the trash, Thorburn et al. [61] found the baling option was 27.8% more expensive as a consequence of the additional handling of the trash.

7.3.2. Comparison of densification systems

It is necessary to compress the trash to increase bulk density and thus to reduce transport costs. Michelazzo and Braunbeck [37]

analysed technical and economical aspects of six sugarcane residue/trash (tops, dry and green leaves) recovery systems, including the cost of sugarcane trash recovery as a function of the field capacity, oil consumption, depreciation, repair and maintenance as well as labour required for the field and transport operations. The trash was left infield after mechanical harvesting of the stalks for approximately 10 days until the moisture content was approximately 20% and the systems evaluated included the following:

- baling (round) of the trash,
- bulk handling to the trash,
- creating briquettes from the trash,
- creating pellets from the trash,
- use of a cotton press to compress and create bales prior to transport, and
- an integrated system where the stalks and trash are transported to the mill and separated at the mill.

The results showed that handling billets and trash together, described as “Integral Harvesting”, has the lowest cost for trash recovery, both for short and long distances, followed by bulk handling of chopped trash, the round baler, the cotton baler and finally the pellet and briquette systems [37].

7.4. Trash recovery costs

The cost of delivering the trash to the mill, which includes the cost of collecting trash from the field, baling the material, and transportation (52% of the total cost), must also include the cost of impacts on the agronomy (43.2% of the total cost) of the trash removal. This includes the loss of recycled nutrients, losses in yield due to soil compaction caused by baling and recovery operations, and the increased cost of herbicides to replace the weed suppressing trash blanket and the cost of separation at the mill, estimated to be 4.8% of the total cost [10,20]. When the above costs were taken into account, Hassuani [20] concluded that, for conditions in Brazil, the separation of the trash and cane in the field and baling and transporting the trash was 41% cheaper compared to a system where the cane and trash are transported together and separated at the mill. The low density and transport cost of the combined cane and trash was a significant cause of the increased cost.

Subsequent to the above study, Filho [17] compared the trash recovery costs for three systems, equivalent to Routes C and Route D in Fig. 1 with no and partial trash extraction as described above. The resulting average trash availability used was 11.65 t of trash ha^{-1} (dry basis). It was assumed that the trash blanket has no nutritive value, has no effect on yield and the environmental benefits of the trash blanket was not considered. The reduced requirement for herbicide when a trash blanket exceeds 7.5 t ha^{-1} was included in the costing. The ARENA systems modelling software was used to simulate activities related to cane harvesting, transportation, weighing, sampling, unloading, milling and several others activities related to the flow of cane. For the costing of mill operations, it was assumed that the initial reference condition (baseline) would be when the mills are processing mechanically harvesting chopped unburned cane, with the harvester separating the trash from the cane and leaving the trash in the field. The production costs considered included soil preparation, planting, harvesting, transport and tillage. The alterative where the cane is mechanically harvested with the separation fans partially turned off and the retained trash is transported with the cane to the mill where it is separated, was found to be the most cost effective system of the systems considered.

The SRDC [59] estimated the costs of six trash recovery strategies, as summarised in Table 4, and found that losses incurred by shredding the cane made it uneconomical and only Strategy 5 showed a positive net benefit.

7.5. Load bulk density and transport

The bulk density of loose trash ranges from 50 to 65 kg m^{-3} and cane stalks bundled with dry leaves have a bulk density in the range from 220–230 kg m^{-3} [47]. Sugarcane leaves have a bulk density of 25–40 kg m^{-3} on a dry basis [25] and trash can be compacted to 242–306 kg m^{-3} using large rectangular balers [47].

Typical differences in whole stalk and billeted cane load densities are shown in Table 5. Hand cut whole stalk and billeted cane will contain additional extraneous matter and hence will require a larger transport capacity [34]. The bulk density of billeted cane is directly related to the length of the billet [34]. Meyer et al. [34] report that for each 1% of extraneous matter transported, the bulk density reduces by 3%.

According to De Beer et al. [8], loading rates decreased by 23–37% for green cane compared to burnt cane. Compared to burnt and topped cane, payloads decreased by 25% and 44% for green (topped) and green (not topped) cane respectively. Relative to burnt topped cane, this resulted in a 16% and 33% increase in the harvesting costs for green (topped) and green (not topped) cane respectively.

In order to improve transport bulk density, the SRDC [59] are considering the impacts of reducing the particle size (billet length and trash particle size), vibration and compaction. Additional power will be required to cut shorter billet lengths and impacts on the quality of the billet and losses may occur. An extractor shredder fan can be used to reduce the trash particle size. Initial laboratory tests indicated that vibration resulted in a 6–20% increase in bulk density but infield results were expected to be less. The use of the shredder fans resulted in improved flow of the material when being tipped and resulted in a 12% to 22% improvement in average bulk density (200–232 kg m^{-3}) which could increase with the use of a topper. However, the use of the shredder resulted in increases in cane loss and resulted in a negative net benefit from the use of the shredder [59].

Table 4
Trash recovery strategies [59].

Strategy	System
1	Whole crop harvesting with extraction fans turned off
2	Modified primary extractor to shred the trash and direct the trash back into the transport vehicle
3	Whole of crop harvesting but with shorter billets
4	Whole of crop harvesting with low fan speeds to remove some trash
5	As for Strategy 1 but with compaction of material in road transport bins

Table 5
Typical differences in whole stalk and billeted cane load densities (after [34]).

Cane	Density (kg m^{-3})
Whole stick cane, tangled and tamped down as in a cane transport vehicle	200.2
Whole stick cane, neatly bundled	400.5
Billeted cane	352.4
Whole stick cane, tangled and loosely tipped into cane carrier	160.2

7.6. On farm processing to increase bulk density and to generate electricity

In addition to the trash recovery routes discussed above, on farm processing of the trash should also be considered as alternative options, as summarised by Rees [48]. These include torrefaction, pelletization, pyrolysis, gasification and bio-digestion. Torrefaction is a type of pyrolysis under specified conditions and can result in a 70% decrease in mass with a 90% retention of the energy of the biomass [63]. Pelletization of biomass increases the bulk and energy density of biomass, facilitates the handling of the material and improves transport efficiency [16,63]. Higher energy density can be achieved by the combination of torrefaction and pelletisation [63]. The products of pyrolysis are liquid, char and gas and the latter two components are sources of energy [63]. Biomass can be thermally converted to fuel gas by a process known as gasification [23]. As an alternative process, an anaerobic bio-digestion system can produce biogas which can be used in internal combustion engines to generate electricity. Uslu et al. [63] found that torrefied and pelletized biomass was the best processed feedstock to generate power at an existing facility, such as at a sugar mill.

8. Trash recovery in South Africa

From the above, it is evident that sugarcane trash recovery is already practiced in some countries (e.g. Brazil and Mauritius). In this section, the potential power generated from sugarcane trash in South Africa is determined and the systems and technology used to recover the trash are assessed for potential application in South Africa.

8.1. Potential trash yield and power generation

The results in Table 3 indicate that the cane trash yield as a percentage of cane stalk yield ranges from 11.2% to 35% in various studies. In South Africa, the most recent value reported is 12.3% and is used in this assessment to determine the yield of trash from sugarcane stalks. The trash recovery efficiency reported in the literature range from 25% to over 80% and a value of 50% is assumed to be attainable in South Africa. This leaves a trash blanket in the field which will have agronomic benefits in most regions of the sugar industry in South Africa. As shown in Table 6, this results in 1.353 million tons of trash available for cogeneration. The energy in trash reported in Table 1 ranges from 2184–2500 MJ t^{-1} and hence a value of 2300 MJ t^{-1} is used in this study. Assuming that the period of operation of the mills is 200 days and no energy loss in the generation process, the energy in the recovered trash could produce 180.1 MW over this generation period. The monetary value of this energy could be determined once the pricing of energy from independent power producers has been established in South Africa.

8.2. Trash recovery systems

For the trash recovery routes presented in Fig. 1, the results from studies reported in the literature indicate that the use of a chopper harvester with limited or no separation of the trash and cane on the harvester and with the trash and cane transported together to the mill is the only economical option. Given that more than 90% of the sugarcane grown in South Africa is manually harvested, and with a large portion grown on terrain where the slopes are not suitable for mechanical harvesting, requires that alternative trash recovery routes need to be investigated for application in South Africa. These include the following recovery routes:

Table 6
Estimation of trash yield and power generation potential for South Africa.

Cane stalk yield	22,000,000	t
Area	430,000	ha
Cane stalk yield	51.2	t ha^{-1}
Potential trash from cane	12.30%	%
Potential trash from cane	6.3	t ha^{-1}
Recovery trash from field	50%	%
Utilisable trash	3.1	t ha^{-1}
Trash left in field	3.1	t ha^{-1}
Required trash blanket	3.0	t ha^{-1}
Available trash at mill	1,353,000	t
Energy from trash	2300	MJ t^{-1}
Total energy delivered to mill	3,111,900	GJ
Length of Milling Season	200	Days
Total power available	180.1	MW

(i) Manual whole stick harvesting with no infield separation of cane and trash: this will require compaction/densification of the cane and trash to improve the economics of transporting the biomass to the mill and the separation of cane and trash at the mill, as indicated for Route A in Fig. 1.
(ii) Manual harvesting and separation of cane and trash in the field, with cane stalks recovered using existing bundling or stacking systems with the trash baled in a separate operation and the bales transported to the mill. This is an adaptation of Route B in Fig. 1 with whole stalks transported to the mill.
(iii) Manual harvesting and separation of cane and trash in the field, with cane stalks recovered using existing bundling or stacking systems and the trash collected and processed (e.g. torrefied and pelletized) prior to transport to the mill.
(iv) Further investigation of mechanical whole stick or chopper harvesting options for use in areas where mechanical harvesting is feasible. From the studies reviewed, only Route D in Fig. 1, i.e. chopped cane and trash transported together to the mill, has been shown to be economically feasible and the economic viability of this option should be assessed for South Africa. However, the use of less expensive and less sophisticated mechanical harvesting systems mounted on tractors, as summarised by Meyer [30], should also be included in the investigation.

9. Discussion and research needs

There are significant environmental impacts of burning sugarcane prior to harvesting. However, the harvesting of green cane has an impact on harvester productivity, irrespective of the harvesting system used. In addition, up to 30% of the energy of sugarcane is contained in the tops and leaves which is lost during burning. Thus, the potential to utilise the energy in the sugarcane trash exists and will require the collection of the trash and transport of the material to the sugar mill where is can be used to cogenerate electricity.

Harvesting systems need to be developed to collect the trash from the field and to transport the material to the mill. Studies in both Brazil and Australia have shown that mechanical harvesting of the sugarcane using chopper harvesters with the trash separation fans turned off or operating at reduced speeds (i.e. Route D in Fig. 1) is the only economically viable method of collection of the trash. The adoption of this approach requires the separation of the billeted cane stalks and trash at the mill as the processing of the combined stalks and trash results in reduced recovery of sugar from the cane stalks.

Currently less than 10% of the sugarcane produced in South Africa is mechanically harvested. Hence, other economically viable systems for the collection and transport of trash will have to be developed for South Africa. Four routes for the recovery of the sugarcane trash have been identified for potential use in South Africa. Three of these routes are based on manual whole stick harvesting with the trash either transported to the mill with the cane stalk, or collected in the field and either baled or processed into a denser form prior to transport to the mill.

The fourth potential route is either mechanical whole stick or chopper harvesting of the cane using either dedicated harvesters or tractor mounted equipment for aiding harvesting. The terrain suitable for mechanical harvesting in South Africa needs to be determined in order to assess the potential area that could be mechanically harvested.

Each of the four routes needs to be costed in detail on a regional basis in order to select the most viable option for trash recovery in South Africa, which may vary between regions and mills. In addition to assessing the economic viability of the different routes, it is also recommended that the net energy balance of trash recovery for cogeneration is also assessed.

The problem of transporting the trash, either on its own or with the cane stalks, is the economic impact of the low bulk density of the trash. Various methods have been investigated to increase the bulk density of the cane and trash for transport. These include baling the trash, cutting shorter billet lengths and the use of vibrators in the transport bins. It is recommended that other on-farm processing of the trash, such as torrefecation and pelletisation, should also be investigated as possible solutions.

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